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LIFE CYCLE SDLM COST MODELS OF THE E-2C HAWKEYE UNDER THE ASPA PROGRAM

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LIFE CYCLE SDLM COST MODELS OF THE E-2C HAWKEYE UNDER THE ASPA PROGRAM

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ABSTRACT

Standard Depot Level Maintenance (SDLM) was conducted on every E-2C in the United States Navy's inventory during a given time interval. The Aircraft Service Period Adjustment (ASPA) implemented in 1985 was designed to reduce the life cycle cost of maintaining an airplane by reducing the number of times the airplane is inducted into SDLM. This changed the maintenance policy from one that is based on a time interval to one that is based on inspection results of airplane material condition. This thesis investigates the long term effect of the ASPA program on airplane life cycle SDLM costs. Through the use of regression models built from data obtained from NADEP North Island San Diego, this thesis analyzes the effect of tour length (the time between SDLM inductions) on both the individual SDLM cost and the life cycle SDLM costs of a typical E-2C. Graphical analysis shows the optimal tour length for a typical E-2C that minimizes the life cycle SDLM costs.

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EXECUTIVE SUMMARY

The Navy's E-2C Hawkeye is a multi-role airplane. The E-2C provides a tactical radar picture of air and sea-going assets and targets of interest. During airstrikes the E-2C provides friendly aircraft information about the target ingress and egress routes, gives bogie information to friendlies and passes battle damage assessments back to the carrier or command ship. In addition to airborne early warning and strike control, the E-2C takes on several administrative type duties while airborne. It functions as a communication relay between ships and planes and is often responsible for maintaining the Link-11 data picture and connectivity. Performing all these duties clearly labels the E-2C as the aircraft carrier's primary C3 asset. Realizing the important role the E-2C plays, the Navy is replacing its current fleet of aging E-2Cs with new E-2Cs. The new airplanes have modifications which use the present airframe but have upgraded avionics, powerplants, radar, and many other systems.

To keep the current E-2Cs in the air and operating safely a scheduled maintenance plan was developed soon after the E-2Cs were built. Under this plan an E-2C is sent to SDLM (Standard Depot Level Maintenance), according to a specified time interval, for airframe rework. In 1985 this maintenance policy, which is one based on time, was changed to a policy that is based on inspection results. The time between SDLMs was no longer based on a fixed amount of time, but instead upon a time that was based upon inspections of the airframe. This new program is called the Aircraft Service Period Adjustment (ASPA). The program was implemented in an effort to save money by decreasing the number of times an aircraft was inducted into SDLM. The total expended maintenance work-hours per airplane was expected to decrease as a result of less SDLM inductions despite the possibility of increased work-hours as a result of the airplane's extended time since the last rework.

The ASPA program has resulted in increased time intervals between SDLMs as well as increased SDLM costs. Analysis of the total cost, measured in maintenance work-hours, shows different time intervals between SDLMs (tour length) that offer the

lowest accumulated SDLM cost over the life of an airplane. The time interval between SDLMs which gives the lowest lifetime cost varies according to the projected lifetime of the E-2C. For projected lifetimes of 20, 25, and 30 years, the time between SDLMs that both gave the lowest cost and was also reasonable was approximately seven to eight years (depending upon the projected airplane lifetime) -- about twice the time interval of the original maintenance program. Lifetime SDLM costs under a program based on a fixed time interval between SDLMs will be cheaper than one based on an ASPA program if the savings attributed to the average increase in tour length under the ASPA program is not substantial enough to outweigh the cost of performing the ASPAs. The decision needs to be made on whether to mandate a fixed time interval between SDLMs or to prescribe a time interval that can be adjusted according to inspection results. A few other factors not analyzed in this thesis that should be considered in the development of a maintenance program are safety of the aircrew and readiness.

I. INTRODUCTION

The E-2C Hawkeye is the United States Navy's premier airborne early warning aircraft. The E-2C provides a tactical radar picture of air and sea going assets and targets of interest During airstrikes the E-2C provides both fighter aircraft and striking aircraft information about the target ingress and egress routes, gives bogie information to friendlies and passes battle damage assessments back to the carrier or command ship. In addition to airborne early warning and strike control the E-2C takes on several administrative type duties while airborne. It functions as a communication relay between ships and planes and is often times responsible for maintaining the Link-11 data picture and connectivity. Performing all these duties clearly labels the E-2C as the aircraft carrier's primary command, control, and communication asset. The aircraft is approaching its maximum service life and is quickly becoming technologically obsolete. Realizing the important role the E-2C plays, the Navy is procuring new E-2Cs with the group 2 modification. This modification uses the present airframe and upgrades the avionics, powerplants, radar, and many other systems -- a significant capability upgrade designed to take the E-2C into the 21st century.

To keep the current E-2Cs in the air and operating according to original specifications, a scheduled maintenance program was developed and adopted in the seventies soon after the first aircraft were placed into service. This program includes routine organizational and depot level preventative maintenance. The standard depot level maintenance (SDLM) entailed sending the plane to the Naval Aviation Depot at NAS North Island, San Diego where it was turned over to a team of NAVAIR engineers and technicians. Once there, the plane received the prescribed maintenance, such as replacing items that were at or approaching their maximum service life, repairing corrosion on the plane that is not repairable at the organizational level, painting the aircraft, and many other actions. Once the aircraft was finished, it was flight checked and turned back over to the Navy and put into service in the fleet. This maintenance performed by NAVAIR had an

average dollar cost, in fiscal year 1985, of $610,000 or an average time cost of 11,000 work-hours.

The first induction of the E-2C airframe into SDLM was scheduled 48 months after the controlling custodian's (squadron, type commander, etc.) acceptance of each new E-2C, and then 36 months after the first SDLM the E-2C airframe was scheduled to be inducted again. Then for the rest of the aircraft's life, it was inducted into SDLM every 36 months. The time between SDLMs is called the operational service period (OSP) or tour and the date of the next SDLM is called the period end date (PED). As we approached the mid 80's, the cost and time to perform a SDLM began to increase while the government was beginning to decrease the real (inflation adjusted) defense budget. In an effort to save money, the aircraft service period adjustment (ASPA) program was introduced to the E-2C and put into place on December 1985. Under this program, an aircraft is inspected by a team of NAVAIR engineers during the period of 180 days prior to or within 90 days past its PED and given a score. These ASPA inspections are nondestructive and look for leading indicators of structural problems as well as corrosion. If an airplane's ASPA inspection score, which is based on the type and number of discrepancies found by the ASPA inspection team, exceeds a mandated score, the plane goes to SDLM as scheduled. If the inspection score is less than the mandated score, the PED is extended 12 months from the original date. Under the current maintenance policy there is no limit on the maximum number of ASPAs a plane can have before a SDLM is required regardless of its ASPA score, so a plane could theoretically remain out of SDLM most of its service life. This extreme case has never happened. The ASPA program takes the previous maintenance program which called for maintenance at prescribed time intervals and changes it into a maintenance program based on inspection. Since an ASPA inspection takes place at the controlling custodian, it has a cost and aircraft down time far less than that of a SDLM. The average cost of an ASPA is approximately 4000 work-hours. This cost includes prepping the airplane for the inspection, opening all the

panels for the inspectors, inspecting the airplane, and finally fixing all the discrepancies found during the inspection.

The ultimate goal behind this change in maintenance policy was to save money by decreasing the number of SDLMs over the life of an airplane. Currently, most of the major commercial airlines have a maintenance policy based on either a time schedule (e.g., every 36 months) or a flight hour schedule (e.g., every 10,000 flight hours). American Airlines, for instance, has a requirement on their fleet of Boeing 767s that when an airplane reaches 7,000 flight hours it undergoes a complete overhaul at the main base in Fort Worth, Texas. This 7,000 flight hour requirement works out to be between one and one and one half years. (Hodge, telephone conversation) Since they are in the business of making money, one would suspect that this was the most profitable maintenance policy to follow. In talking with the Wing 12 Maintenance Officer about the present maintenance policy for the E-2C, he indicated that currently this policy might be costing the Navy more time and money than the old scheduled maintenance policy and should therefore be revised. This feeling was supported by the E-2C program manager at the NADEP facility at NAS North Island that conducts the ASPAs and SDLMs. In a research memorandum (Levy, 1991, p. 1) it was stated that the workload at the depots had increased significantly since the start of the ASPA program and that it was suspected that the overall cumulative SDLM costs had increased.

This thesis will first show the costs of all the SDLMs from the start of ASPA in 1985 to the end of fiscal year 1994. Once it is clear that these costs are increasing, we will develop a model that will predict SDLM costs based on explanatory variables that are chosen from the data base made available to us from the Grumman facility at NAS North Island. With the model, we will show the accumulated SDLM costs over a 20, 25, and 30 year life cycle of a typical E-2C. Graphical analysis on the accumulated SDLM costs will indicate the optimal maintenance policy for a given life cycle length.

II. PROBLEM STATEMENT

The goal of the ASPA program was to decrease SDLM costs by increasing the time interval between SDLMs. This time interval is referred to as tour length. It is the thought of the Wing-12 Maintenance Officer and the NADEP E-2C program manager at NAS North Island that since the planes are being kept out of SDLM for a longer period, more discrepancies are going unrepaired, so that when they finally do go into SDLM, more maintenance is needed. This not only drives up the cost of a SDLM, but perhaps more importantly, increases the down time of the aircraft thereby affecting squadron readiness. In fiscal year 1994 the average SDLM cost in dollars and time was $24.4 million and 34,737 maintenance work-hours, respectively, an increase of over 300 % in dollars and an increase of over 200 % in work-hours from 1985.

It is also believed by engineers and technicians at NADEP, NAS North Island, that the cost of SDLMs is also being driven up as a result of the increased amount of time spent on modifications to the airplane. The more a plane is exposed by opening panels that would not normally have been opened during a routine SDLM for modification work, more discrepancies are being found. For instance, if a plane needs a modification that requires drilling fastening holes in the airframe, the area of installation must meet certain specifications, such as metal density, for attaching parts to the airframe. The place of attachment prior to the modification could be within specification limits for that section of aircraft. Now that more holes must be drilled into airframe at the point of attachment to accommodate the modification, the plane is out of specifications, due to the decrease in metal density, as a direct result of the increased number of holes in the structure. Bringing the airplane up to the specifications required of that particular modification will require that more work (in this case metalsmith work) be performed at the SDLM, thereby increasing the cost of the SDLM.

The total lifetime SDLM cost per airplane is believed by some to be greater under the ASPA program than it would have been under the previous policy of scheduled maintenance. It is the purpose of this paper to analyze SDLM data supplied by NADEP at

NAS North Island and prescribe the optimal maintenance policy for a typical E-2C. This policy could then be used on the E-2Cs that are currently in service in the fleet and the E-2Cs that are due to be put in service in the future. It is not the intent of this study to reveal a policy that will be the best for each individual E-2C, but instead a policy that can be used on the typical E-2C. This definition of the typical E-2C can then be used on the entire fleet of E-2Cs as a group.

Other research in SDLM/ASPA cost analysis has produced different results than we would expect from taking into account the thinking of the Wing-12 Maintenance Officer and the NADEP E-2C program manager at NAS North Island. In a research memorandum (Levy, 1991) published in 1991 the cost effects of the ASPA program were studied for five Navy aircraft types, one of them being the E-2C. The paper, using data collected from 1984 to 1989, concluded that holding aircraft age constant, an increase in tour length did not significantly increase SDLM costs. The paper also concluded that the lifetime costs of an average aircraft experiencing a fewer number of SDLMs, even though they may be more costly than more frequent SDLMs, was in fact a savings over more frequent SDLMs. The goal of our study is also to analyze the effects of the ASPA program on SDLM costs and, in doing so, to find an optimal maintenance policy for the E-2C. We will have the luxury of added history for our study -- our data base will reflect data collected from 1985 to 1994, approximately five more years worth of data, which will double the size of the E-2C data base used in the earlier study by Levy.

III. EXPLANATORY VARIABLES

To analyze the effects of the ASPA program on SDLM costs, we needed accounting data that would perhaps show some cause or effect of increased SDLM costs. We turned to NADEP, NAS North Island for help in getting the data we needed for the study. The data available was individually recorded SDLM costs for each aircraft that was inducted into SDLM. The data was tabulated by fiscal year. Total SDLM costs were broken into two categories of variables, dollar and man-hour figures, as well as the portion of those variables spent on modifications. Other data such as tour length and age were not gathered from a single source, but from numerous documents made available to us by NADEP. The data was then condensed and put into a spreadsheet for analysis. Appendix A contains the data used for our study. The data obtained from NADEP North Island, CA is for fiscal years 1985 through 1994. Data for SDLMs conducted prior to 1985 were not available.

For purposes of this study SDLM costs will be measured in maintenance work-hours. This alleviates the need for inflation tables and knowledge of the monetary accounting practices used at that time, thereby adding more accuracy to the results. Also one can look at SDLM costs then as a form of inverse readiness -- the longer an airplane is in SDLM, the less it is at the squadron thereby decreasing squadron readiness. Analysis of the data will yield a regression model or models that can be used in further study or cost analysis of the ASPA program and its effects on SDLM costs.

Looking at Figure 1, a plot of SDLM cost expended per airplane inducted into SDLM, one can see a definite trend towards increased cost over time. In 1986, one year after the ASPA program was initiated, a slight rise in man hours is noticed. But for the most part, the average SDLM cost remains fairly constant around 11,000 hours for the next three years. However, the full effects of the ASPA program start to be seen in 1990 with a significant upward trend in cost that continues, for the most part through 1994 and this is intuitively what one would expect to see for the following reason. A maintenance program that previously had a three year cycle that has just been increased to a variable

number greater than 3 years will not start to experience the full effects of the change in policy for at least a three year period but more likely a four or five year period. Since the pre-ASPA scheduled maintenance program had a cycle time of three years (an airplane's OSP), one would expect at least a three year delay to see the effect of ASPA on the entire group of airplanes. At three years past the inception of ASPA the data would reflect the effects of ASPA inspections on SDLM costs, but more dramatic effects would not be expected to be seen for an additional few years. By the end of a five year period after the start of the ASPA program, each airplane has had between two and five ASPA inspections, so at this point in time the ASPA program itself could be viewed as having settled into more of a steady state than three years after its start and even more so than immediately after its inception. Data taken following this five year period after the start of ASPA could be viewed as more coherent data since it was not collected during a period of change, but instead collected during a period where the maintenance policy had been in

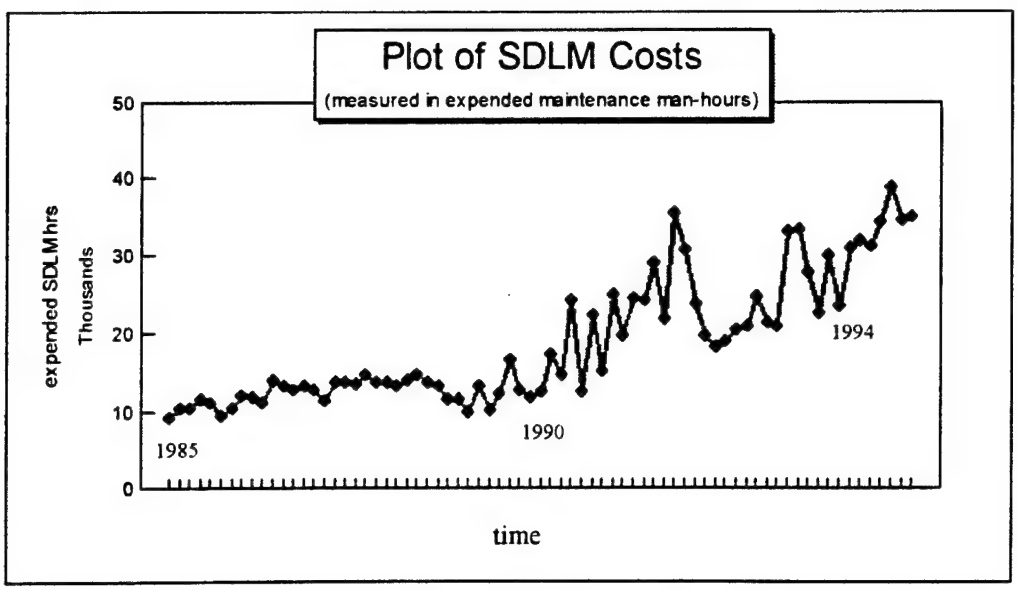

Figure 1. A Plot of SDLM cost verses time shows increasing SDLM costs over time as well as a change in the slope of the increase of SDLM costs around 1990.

effect for four years. It is this data taken from the last five years that would most dramatically reflect the effects of ASPA inspections on SDLM costs.

Once it was evident that SDLM costs were increasing, we started looking for explanatory variables for these increases. Intuitively one would expect aircraft age to affect SDLM costs. As aircraft age increases, the airframe and various components accumulate more fatigue and wear which increases the amount of maintenance needed on these aircraft. Another explanatory variable would be tour length (time interval between SDLMs). When an aircraft comes out of SDLM, the previously overly fatigued and worn components have been replaced or repaired. One could almost view an airplane just out of SDLM as a newer airplane; the SDLM is similar to a stochastic renewal process. As the tour increases so does the accumulated fatigue and wear on the airframe and various components. Once this wear deteriorates components past an acceptable level (deterioration level is determined at the ASPA inspection), the component must be repaired or replaced. Another argument for including tour length is that it is directly affected by the ASPA program. Therefore, if we could develop a robust model involving tour length, we could make conclusions about the effect of ASPA on SDLM costs. Total number of flight hours on the aircraft could also be an explanatory variable. However, as one would expect, that number is highly correlated to the age of the aircraft and to tour length. (The last two statements assume that on the average each squadron flies its airplanes as much as any other squadron.)

Another possible explanatory variable for SDLM cost is the number of work-hours spent during SDLM on modifications. Use of modification work-hours spent on the airplane during SDLM is justified by the earlier statement about the observed positive correlation by the Wing-12 Maintenance Officer and the NADEP E-2C program manager. Since this is time series data that is subject to the effects of serial correlation, the final variable to include is a time variable. The time variable we chose was the number of years since 1945 to an airplane's induction into SDLM. For example, if an airplane was inducted into SDLM during fiscal year 1985, the associated time variable would be 40 years. Not

only will this variable potentially subsume the effects of serial correlation, but it will also incorporate any time dependent influences on the data that were not directly accounted for such as contract negotiations, state of the economy, or political factors that might effect SDLM costs.

The data supplied by NADEP, NAS North Island shows that over time, SDLM costs have been increasing. Around fiscal year 1990, the rate of increase of SDLM costs changes, apparently showing the effects of the ASPA program. Tour length was selected as one of the explanatory variables that would show the effect of ASPA on SDLM costs since it is directly affected by the ASPA program. Aircraft age and the number of work-hours spent on modifications during SDLM are two other explanatory variables we will use for our model. Finally a variable that tracks time, namely the number of years since 1945, will be the final variable for the model.

IV. REGRESSION MODELS

To analyze the data from NADEP, we need to develop a model. The goal behind the model is to gain insight on the driving factors behind the increase in SDLM costs, then to take these factors and do long-range analysis to determine an optimal maintenance policy. For the type of data we have and the model analysis characteristics we are looking for, a regression model seems to be the best for the study since it will give us insight on the effect of each explanatory variable on SDLM costs. Numerous regression models were looked at for both their statistical strength and for their intuitive insight. The best ones were chosen for inclusion in the long-range cost analysis.

A. MODEL 1

With a set of possible explanatory variables, we employed O.L.S. (ordinary least squares) and MINITAB release 9.2 for the regression. Candidate models were first chosen by regressing the best variable subsets, out of the variables described in Chapter III (tour length, aircraft age modification work-hours, and years since 1945), on SDLM costs. This was done by looking at the best four single explanatory variable models, then the best four dual explanatory variable models, and continuing until finally looking at the best model that contained all the explanatory variables out of the set of possible variables. Included in the variable list used above were the variables raised to the power of two. This was done to find a variable or combination of variables that would explain the increased SDLM cost that appears to increase somewhat more than linearly as time progresses. Various models of different numbers of explanatory variables were then compared to find not only the best statistical model but also one that intuitively makes sense. The adjusted R^2 value and the standard error of the regression were the statistical measures used for model selection while intuition and common sense were used to temper the choice. The best model chosen is:

$$\textit{SDLM cost} = -107117 + 63.25\ \textit{Tour} + 13.62\ \textit{Age} - 0.31\ \textit{Mod hrs} + 2241.7\ \textit{Years since 1945}$$

The model is statistically strong. The coefficient of determination (R^2) is 0.79 and the adjusted R^2 is 0.78, both of which are acceptable by usual standards. The F-statistic associated with the significance of the regression is 63.83, which has a P-value of 0.00; we conclude that the regression is significant. T-statistics on the null hypotheses that individual slope coefficients are equal to zero show that three of the five variable coefficients are significant at the 0.00 level, one is significant at the 0.12 level, with the worst being significant at the 0.3 level. A Durbin-Watson statistic of 1.31 lies just below the inconclusive region between 1.37 (the largest value in the region of positive indication of serial correlation) and 1.59 (the smallest value in the region of no serial correlation) at the 0.01 significance level. This indicates that there is a possibility for serial correlation in the data. The standard error of SDLM cost for this model is 3824.2. This value was not the lowest of all the models tested, but was not far enough away from the lowest value of 3629.7 to make a significant impact on the decision of which model to choose. A MINITAB printout with the above information, in more detail, is given in Appendix B. A comparison plot of the actual data and the fitted values, Figure 2, shows that the model fits the data fairly accurately.

Intuitively, the model makes sense. The coefficient of each explanatory variable gives the direction and magnitude of the effect of that variable on SDLM cost holding all other variables constant. *Tour* and *age* both have positive coefficients indicating an that increase in either one of these variables will increase SDLM costs. In fact the coefficient for *tour* is roughly four and one half times more than the coefficient on *age*. This would mean that holding all other variables constant, tour length has four and one half times the impact on SDLM cost than does the age of the aircraft since both are measured in years. *Mod hrs* (hours spent on modifications) has a negative coefficient indicating that an increase in hours spent on modifications will decrease SDLM cost. This goes against the hypothesis made by the Wing-12 Maintenance Officer and the NADEP E-2C program manager. Several different models were tested to see if any of those would have similarly strong statistics and a positive coefficient for *mod hrs*, but none were found. Multiplying

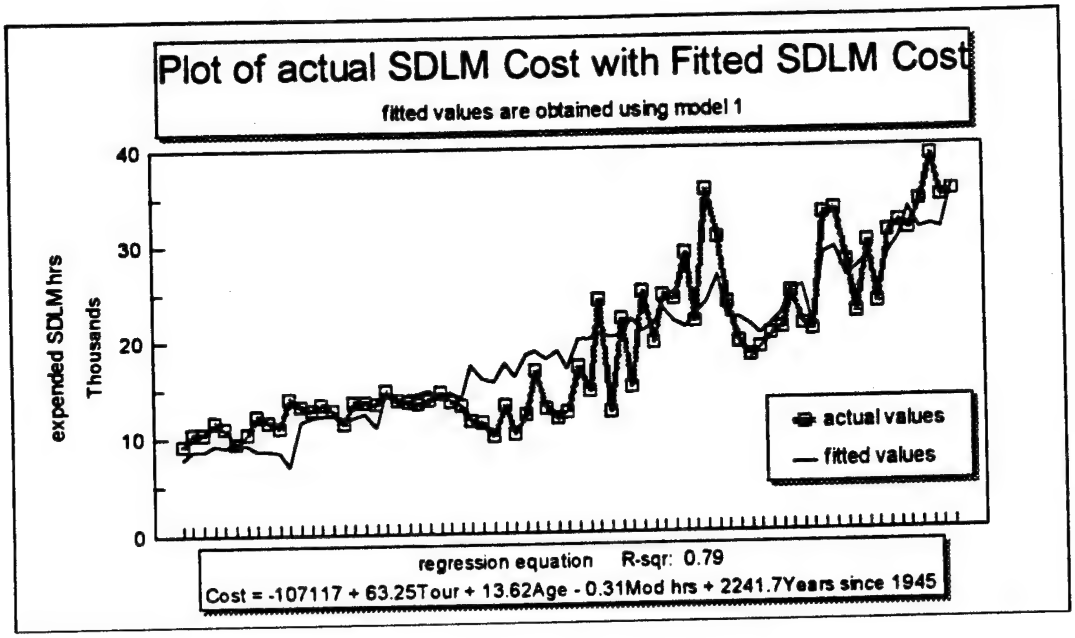

Figure 2. Plot of Model 1 SDLM Costs. A comparison plot of the actual SDLM costs and the fitted SDLM costs using Model 1.

the value of the coefficient and the average number of maintenance work-hours spent on modifications to the airplanes, the effect of this variable on SDLM costs, holding all other variables constant is only -84.7 maintenance work-hours per SDLM. Even though the effect of this variable is small and contrary to popular belief, it is included in the model based on its T-statistic and associated P-value contained in Appendix B. The coefficient for the time variable *years since 1945* is positive and is the largest, indicating that this has the largest effect out of all the other variables on SDLM costs. Given the relatively small number of variables to choose from in our data, it is not surprising that this variable has the largest coefficient. This variable picks up all the unexplainable effects that the other variables do not, which in many cases with this type of data, can be quite numerous. Now that the model is given, it would be a good time to explain why the date of 1945 was chosen for the variable that marks time instead of a more intuitive date such as 1985 (the start of the ASPA program). If we were to use 1985 as the start point for our time

variable and use that model for prediction and long-range life cycle cost analysis, the time variable would behave differently in the first few years (i.e., doubling in value every couple of years) than it would 20 or 30 years later. For example if we want to predict SDLM costs on a particular airplane for the year 1995, the time variable has now increased form one to ten, a 900% increase in magnitude. But if we use 1945 as the start point for our time variable, the same interval from 1985 to 1995 does not show a 900% increase in magnitude, but instead only a 29% increase. By using 1945 as the start date of the time variable, we avoided these orders of magnitude jumps that would have plagued the long-range life cycle cost analysis. Model 1, developed by O.L.S. regression and chosen as a result of statistical and intuitive comparison, is the best single model for explaining SDLM costs for the entire data set.

B. STRUCTURAL CHANGE

Looking back to Figure 1, one sees a possible change in both the intercept and the slope of the trendline around the point that coincides with fiscal year 1990. This indicates that perhaps the notion of developing just one model for the entire data set might not be the best thing to do, especially since we are mostly concerned with the data that was taken a few years after the ASPA program was put into place. One would think that the explanatory variables in the data at the inception of ASPA and for the next five years would have different magnitudes than those in the data taken over the last four years. This idea shows the appropriateness of analyzing the data to see if it would be significant to treat the data as two different subsets.

To test for this possible change in the intercept and the coefficients of the explanatory variables, we did a test for structural change commonly referred to as the Chow test (Greene, 1993, pg. 211). The test involves running two different regression models using O.L.S.: an unrestricted model which allows the intercepts and the explanatory variables to be different, and a restricted model which does not allow different intercepts or coefficients in the model. The unrestricted model is actually two models regressed from the data being split into two subsets at the point of believed change. The

total sum of squared residuals from this model will be the sum of the two residual sums of squares from the two individual models. The restricted model is simply a single model regressed on the entire set of data. The F-statistic associated with the test for structural change is then compared to the tabled critical value for the five percent significance. The null and alternate hypothesis's as well as the F-statistic that are associated with this test are shown below.

H_0: the regressions are the same (the slopes and the intercepts are the same)

H_a: the regressions are different (at least one slope or intercept is different)

The associated F-statistic for the null hypothesis is:

$$F = \frac{(ESS_I - ESS_{III}) \ / \ (pk-k)}{(ESS_{III}) \ / \ (N-pk)} \quad ,$$

where ESS_I and ESS_{III} are the residual sum of squares from the restricted model and unrestricted model, respectively, and they are divided by the appropriate degrees of freedom.

If we are able to reject the null hypothesis in favor of the alternate hypothesis, then we can say that the two regressions are not the same and the data should be analyzed as two different subsets. It is important to note that this test for structural change does not indicate which coefficients have changed, it only indicates that some coefficients or the constant term has changed by basing the model on two subsets of the data instead of the one data set as a whole. To find out which coefficients have changed, simply perform O.L.S., with the same set of explanatory variables, on each of the two subsets and compare the constant terms and the like variable coefficients to determine the amount of change in the influence of that particular variable on SDLM costs. (Greene, 1993; Boger class notes, Oct. 1994)

In order to find the optimal point of structural change, we need to do sensitivity analysis around the area of suspected change. The best variable to do this on is the time variable because then we can see when the change takes place on our time plots of SDLM costs. The point that yields the highest F-statistic in the Chow test will be used to split the

data into two different sets, provided it is greater than the tabled F-statistic. Since our data was blocked into fiscal year groups (i.e., the variable *years since 1945*), the point of structural change in time must inherently lie between two consecutive fiscal years. However, since fiscal year blocks could contain up to 11 airplanes, the best point of structural change can not be found since only the year closest to the best point can be determined. If the point of structural change lies in the middle of a fiscal year, it might go undetected if the F-statistic between that particular year and the one prior to it or after it is not significant. To alleviate this potential not to detect structural change, as well as to find the best point of structural change, we numbered the airplanes inducted into SDLM consecutively from 1 to 73; this we called the airplane's sequence number. The models were then run using the sequence number as the time variable instead of the number of years since 1945.

F-statistics were then calculated for numerous points around the area of suspected change. Appendix C shows the sensitivity analysis and F-statistic calculations used for the above mentioned procedure. The best point to chose to split the data into two subsets is the two sequence numbers that yielded the greatest F-statistic value. The point at which the greatest value for the F-statistic occurred in the middle of fiscal year 1991, at sequence number 46, with an F-statistic value of 3.163. The associated tabled F-statistic, $F(0.05,10,53)$ is 2.03 (Greene, 1993, pp. 734-735), which is lower than the calculated F-statistic, therefore we can reject the null hypothesis and conclude that there are two different regressions that are appropriate for the data. Figure 1 shows, that at about the middle of fiscal year 1991, there is a visual difference in both the slope and the intercept of the data. The significance of this point, other than the fact that it is the start of a different set of data with a different regression model, is that here is where the SDLM cost changes the rate at which it is increasing. The ASPA program was started in 1985, but one would not expect to see any change in costs as a result of the program for a few years. This point indicates when the ASPA program has started to affect the SDLM costs. Prior to this point of structural change, the average tour length was 4.4 years and after this point

the average tour length increased to 7.7 years. It is now clear that the data should be divided into two subsets and these subsets be used for the next model.

C. MODELS 2A AND 2B

Now with the data split into two subsets, regressions were run using O.L.S. and MINITAB version 9.2 on the same set of explanatory variables used in Model 1. For ease of reference, the data and models obtained from that data will be named as follows: the entire set, sequence number 1 through 73, Model 1; from sequence number 1 through sequence number 45, Model 2a; from sequence number 46 through 73, Model 2b. Models 2a and 2b are:

$$\begin{aligned} \text{SDLM } cost_{2a} &= 8839 + 27.51\ Tour + 23.54\ Age + 0.69\ Mod\ hrs \\ &\quad -15.30\ Years\ since\ 1945 \end{aligned}$$

$$\begin{aligned} \text{SDLM } cost_{2b} &= -68670 + 53.65\ Tour + 13.57\ Age - 0.48\ Mod\ hrs \\ &\quad + 1641\ Years\ since\ 1945 \end{aligned}$$

Statistical analyses on Models 2a and 2b shows that the two models are not as robust as Model 1 presented previously (see Appendix B). The R^2 and adjusted R^2 values are lower than Model 1. The values of the coefficients of variation are roughly equivalent in all three models. The Durbin-Watson statistics are, however, significantly different. The Durbin-Watson statistics for the two models are closer to the value of 2.00, indicating that there is no serial correlation at the 0.05 significance level for both Models 2a and 2b. Table 1 shows a statistical comparison among the three models. A comparison plot of the actual data and the fitted values in Figure 3 shows an accurate fit of the model with the actual data.

The signs of the coefficients in Models 2a and 2b are similar to those in model 1, with one exception; the sign of the *mod hrs* coefficient in Model 2a is positive instead of negative. This agrees with the hypothesis drawn from the Wing-12 Maintenance Officer and the NADEP E-2C program manager. There is again the discrepancy between popular opinion and the model in the sign of the *mod hrs* coefficient in Model 2b. The coefficient is negative indicating that the number of maintenance work-hours spent on modifications

	Model 1	Model 2a	Model 2b
R^2 / adj. R^2	0.79 / 0.78	0.61 / 0.58	0.66 / 0.60
Standard Error of the Regression	3,824.2	2,243.1	3,820
Coefficient of Variation	0.2	0.12	0.2
F-statistic / P-value	63.83 / 0.000	15.93 / 0.000	11.12 / 0.000
Durbin-Watson Statistic	1.31	1.96	1.78

Table 1. Statistical Comparison of Three Models. A statistical comparison between three different models - the model for the entire set of data (Model 1), a model for the first 45 SDLMs in the set (Model 2a) and a model for the last 28 SDLMs in the set (Model 2b).

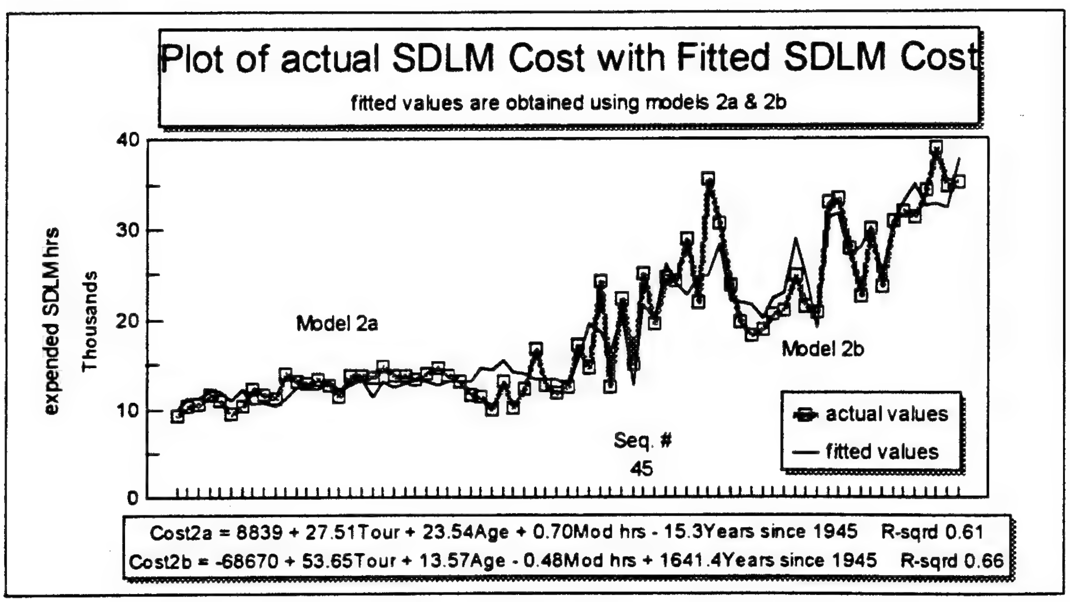

Figure 3. Plot of Models 2a and 2b SDLM Costs. A comparison plot of the actual SDLM costs and the fitted SDLM costs, using Model 2a for sequence numbers 1 through 45 and Model 2b for sequence numbers 46 through 73.

negatively influences SDLM costs, whereas it is believed that the number of maintenance work-hours spent on modifications positively influences SDLM costs.

There is an informative comparison between the coefficients for *tour* and *age* in Models 2a and 2b. In Model 2a, the coefficients are roughly the same indicating they influence SDLM cost equally, holding all other variables constant. In Model 2b, the coefficient for *tour* is about four times larger than the coefficient for *age*, indicating that *tour* has about four times as much influence on SDLM cost as *age*. This change in variable coefficients takes place at the point of structural change determined earlier. At this point we argued that it is here where the full effects of ASPA on SDLM costs are seen. The direction and magnitude of these effects can be calculated by subtracting the variable coefficients of Model 2a from the coefficients of like variables in Model 2b. By doing that we see the largest change in coefficient magnitude in *years since 1945*. This again is a variable that acts as a 'catch-all' variable accounting for all the unknown effects in SDLM costs during those particular time periods. Some explanation for the increase in magnitude could be that the way NADEP accounted for maintenance work-hours changed, or it may be the result of a combination of political and economic factors that were affecting both NADEP, the government, or their business relationship at the time. The second largest change in variable coefficient occurs at the variable *tour*. After the point of structural change we see the full effects of the ASPA program on SDLM cost. As SDLM costs rise so does the coefficient of *tour*. The tour length in Model 2b has a coefficient that is almost twice as large as it was in Model 2a. This says that past the point of structural change where the effects of the ASPA program are visible in the data, the tour length which is directly effected by the ASPA program now has twice the impact on SDLM costs as it did prior to the point of structural change. From Model 2a to Model 2b the variable *age* decreased about 50%, indicating that the age of the aircraft was playing a less important role in the SDLM costs. So as the importance of aircraft age decreased about 50% from Model 2a to Model 2b, the importance of the tour length increased about 100%. Models 2a and 2b, developed by O.L.S. regression and chosen as a result of

statistical and intuitive comparison, are the best models for explaining SDLM costs for each of the two subsets, determined by structural change analysis, of the entire data.

D. MODEL SELECTION

The goal of developing a model for the SDLM data was two fold, to predict long run life cycle SDLM costs and to gain some insight to the causes for the increase in rise of SDLM costs over the last four years. Model selection among the three models presented was done both on a basis of the statistical strength of the model and the insight the model provided to the problem solution -- does an increase in tour length as a result of the ASPA program have a greater increase on SDLM cost than the savings of doing fewer SDLMs? Model 1 seems like it would be a good choice to use since it has the convenience of being a single model that was developed from the entire data set. This convenience is also a drawback in the sense that the effects of the entire data set are captured in the model. This would be fine if the data set we would be applying the model to for future cost predictions was basically the same, but this is not the case. The historical data contains the effects of all the explanatory variables during the time the ASPA program was just getting started as well as the time period when the ASPA was in a steady state four or five years later. The E-2Cs in the fleet now are operating under a maintenance program that is already in the ASPA steady state. Using Model 1 on these airplanes for future life cycle SDLM cost predictions would be a mistake since these airplanes will not be undergoing a start-up period for the ASPA program like the airplanes in the historical data. However, Model 1 should not be totally discounted as being useful. Once a model is decided on for use in life cycle SDLM cost predictions, it would be beneficial to use similar prediction results from Model 1 as a comparison tool against the final model.

Models 2a and 2b have the benefit of being derived from the data being split into two distinct subsets. This proves to be of relevance when used in long run life cycle SDLM cost predictions. Since the E-2Cs that will be used for life cycle SDLM cost predictions are already under an ASPA program that has reached a steady state, Model 2b will be used for analyzing life cycle SDLM costs. Model 2a is beneficial to this study in

comparing to Model 2b for the effects the ASPA program had on the different explanatory variables. Model 2a could also be used to study SDLM costs immediately after the start of an ASPA-type program, if such a program were considered for implementation in the future.

The set of explanatory variables (*tour*, *age*, *mod hrs*, *years since 1945*) were used to develop two models for SDLM costs. Model 1 used the entire data set, where Model 2 split the data set into two subsets. Both of the models are statistically strong and intuitively logical and model the same dependent variable, SDLM cost. These models show that there is not a single model that is both accurate for the data and useful to the study. Model 2b is chosen for the life cycle cost analysis, however similar results from Model 1 will be used for comparison. In the next chapter, these two relationships will be analyzed for the policy implications of the models.

V. RESULTS AND CONCLUSIONS

The goal of this study is to examine the scheduled maintenance program of the E-2C under varying tour lengths imposed upon it by inception of the ASPA program in fiscal year 1985. In the previous chapters we discussed the different variables that we obtained from the data supplied by Grumman located at NADEP, NAS North Island. *Tour*, *age*, *mod hrs*, and *years since 1945* were the explanatory variables we decided to use in our models. With these four variables we developed two SDLM cost models using regression techniques on the data. Model 1 used the entire data set from fiscal years 1985 to 1994. This model takes into account not only the effects of the ASPA program once it settled down into a steady state, approximately from 1989 and on; but also the start-up effects, those years immediately after the start of the ASPA program. This model we determined to be too encompassing for a study that involves airplanes that are already under the ASPA program and have been for ten years. The second model we developed from the data set being split into two subsets. Structural change analysis gave us the optimal point to split the data into two groups that represented the two different phases of the ASPA program, the start-up and the steady state phases. Model 2a is the model developed using the data from the start-up phase of the ASPA program, and Model 2b is the model developed from the data in the steady state phase. Model 2b,

$$\begin{aligned} SDLM\ cost_{2b} &= -68670 + 53.65\ Tour + 13.57\ Age - 0.48\ Mod\ hrs \\ &\quad - 1641\ Years\ since\ 1945\ , \end{aligned}$$

is the model of most interest to us for life cycle SDLM cost analysis since it was developed using a data base that has similar characteristics as the one we will use for the life cycle analysis.

A. LIFE CYCLE SDLM COST

The question we want to answer is, "Has the ASPA program increased SDLM costs incurred by each airplane over its expected life cycle?" To answer that question we must look at what the ASPA program directly affects as far as our explanatory variables

are concerned. *Tour*, which is the time interval between consecutive SDLMs, is directly affected; after all, the idea behind ASPA is to extend the period between SDLMs by changing what was a previously scheduled maintenance program into one that is now a maintenance program based on inspection. *Age*, which is the age of the aircraft, is independent of the ASPA program; an aircraft will age if or if not the ASPA program is in effect. *Mod hrs*, the number of maintenance work-hours spent on a particular airplane for installing modifications during a SDLM, is independent of the ASPA program. Airplanes require certain modifications from time to time and the ASPA program has nothing to do with modifications to the airplane. Finally, like *age* and *mod hrs*, our time variable, *years since 1945*, is not affected by the ASPA program. It is simply a count of the number of years since 1945 to the induction into SDLM of a particular airplane. Out of the four variables, only one is directly affected by the ASPA program and that one is *tour*.

The most intuitive way to study life cycle SDLM costs is to take a "typical" airplane, which we will define later, and see what the accumulated SDLM costs would be over its expected lifetime. This should be done for different tour lengths to determine which tour length gave the lowest accumulated life cycle SDLM cost, and the one that did should be the tour length of a typical airplane between SDLMs. We define a typical airplane as having the average SDLM characteristics of all the airplanes in the data set from fiscal years 1985 to 1994. This would specifically apply to our model in assigning a value to the number of maintenance work-hours spent on modifications for a typical airplane (*mod hrs*).

We will start the analysis in the present fiscal year, 1995. The age of the typical airplane we will assume to start at one, starting with a new airplane. The *age* variable will increase throughout the life cycle analysis and will stop increasing at the expected lifetime of the airplane. The number of modification hours spent on the typical airplane will be the average age of the airplane over its expected lifetime multiplied by the mean number of modification hours spent on each airplane per fiscal year in the data set from fiscal years 1985 to 1994. This value for *mod hrs* will give us the average number of modification

hours a typical airplane would experience over its lifetime. The variable *years since 1945* will increase in the same way as *age*, however it will be starting at the value 50 instead of one. *Tour* will remain constant for analysis of each life cycle, but will vary between analyses. Using Model 2b and the values for the variables we stated above, various life cycle SDLM costs were computed and displayed graphically. We did these calculations for an expected lifetime of 20, 25, and 30 years. See Appendix D for a sample life cycle SDLM cost calculation.

1. 20 Year Expected Lifetime

Using an expected lifetime of 20 years we perform the above calculations using both Model 2b and Model 1. Model 1 is used purely for comparison purposes with Model 2b. Figure 4 shows the results. The graph's x-axis starts with tour length equal to two, which was done to keep the resolution of the graph in the higher values of tour length discriminative. The accumulated SDLM costs of a typical airplane with a tour length of one year was 640,762 maintenance work-hours, slightly less than two times that of an

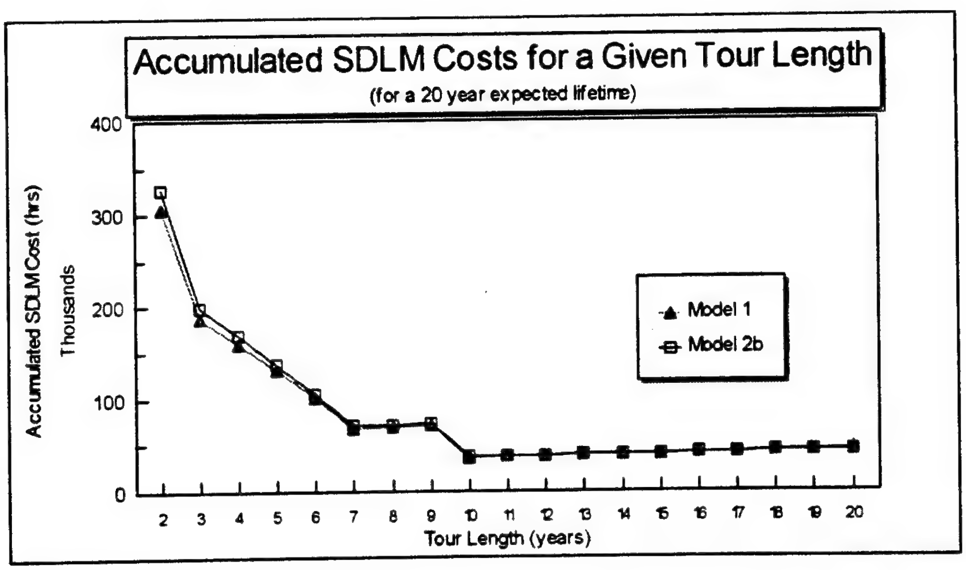

Figure 4. 20 Year Accumulated SDLM Costs. This plot shows the accumulated SDLM costs as a function of tour length during a period of twenty years for a typical E-2C .

airplane with a tour length of two years. The behavior of the graph is a combination of a smooth curve broken up by steps. The steps are a result of the whole number of SDLMs conducted in a lifetime instead of using fractional numbers of SDLM. For example, if the tour length was six years and the expected lifetime of the airplane was 20 years, the airplane would be inducted into SDLM three times during its lifetime, not 3.33. After the third SDLM it receives at its 18 year old point, it would not be inducted into SDLM again, given the tour length is six years thereby keeping the total number of SDLMs over the expected lifetime equal to three.

At tour length equal to three years, the slope of the curve starts to level off indicating that the marginal returns from increasing tour length are starting to decrease. When tour length is seven years the slope of the curve changes directions. This point is a local minimum which equates to a local optimum since we are seeking the minimum accumulated SDLM costs. When tour length is extended to nine years the slope again changes direction and the accumulated SDLM costs decrease until tour length is ten years and costs start to rise linearly. Another local minimum occurs at tour length equal to ten years. The graph has two local minimum or two local optimal points. This would indicate that tour length should be either seven years or ten years, with ten years having the lowest accumulated SDLM costs of the two by a factor of 0.5. So in this case the optimal tour length that would minimize accumulated SDLM costs over a twenty lifetime of a typical E-2C should be ten years. This might seem like an unreasonably long period of time between SDLMs given the average tour length of all the E-2Cs, since the point of structural change discussed in Chapter IV is 7.7 years, but it is attainable (the maximum tour length observed was 11 years). Given the historical average, perhaps a tour length of seven years (the other local optimal point) would be a more realistic tour length. The increased cost of performing a SDLM every seven years instead of every ten years is projected to be 33,663 work-hours over the lifetime of the airplane, a relatively small number that is about the cost of a single SDLM. Notice that Model 1 tracks accumulated SDLM cost almost exactly the same as Model 2b.

2. 25 Year Expected Lifetime

Using 25 years as the expected lifetime of the typical airplane, we performed the calculations mentioned previously and displayed the results graphically in Figure 5. Accumulated SDLM costs were also calculated and plotted for comparison to the results obtained from Model 2b. The graph's x-axis starts with tour length equal to two in order to improve the resolution of the graph in the higher values of tour length. Since a tour length of one year gave an accumulated SDLM cost of approximately 913,718 maintenance work-hours, about two times more than tour length of two years, it was not relevant in our minimum cost tour length search. The graph behaves very similarly to the graph for an expected lifetime of 20 years, but there a few differences that are worth mentioning. Instead of having two local optimal points Figure 5 has three, one at seven, nine, and 13 years. A tour length of 13 years is unreasonable, given the average tour

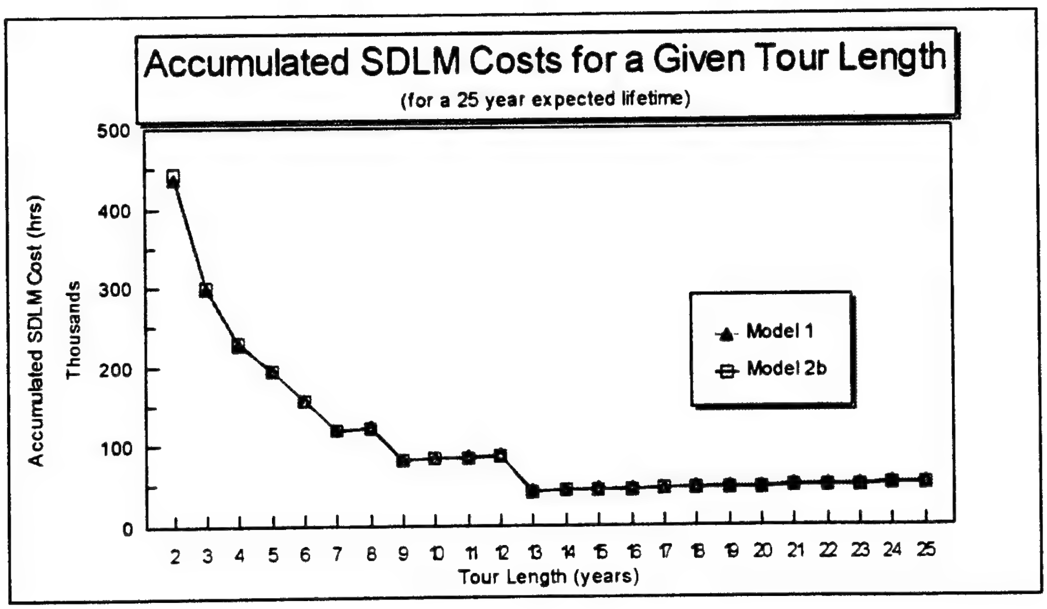

Figure 5. 25 Year Accumulated SDLM Costs. This plot shows the accumulated SDLM costs as a function of tour length during a period of twenty five years for a typical E-2C.

length of E-2Cs since the point of structural change is 7.7 years. However, both a seven year tour length and a nine year tour length should be considered. On a typical E-2C, the lifetime savings, over a twenty five year period, of doing a SDLM every nine years vice every seven years is projected to be 37,903 maintenance work-hours.

3. 30 Year Expected Lifetime

With the expected lifetime of a typical E-2C, we performed the same series of calculations as in the previous two cases. Figure 6 shows the results using Model 2b as well as the results obtained using Model 1 for comparison. As in Figures 4 and 5 the x-axis of the graph starts with the value of two to increase the resolution of the graph in the larger values of tour length. Here we see three local optimal points, when tour length is eight, 11, and 16 years. We can discount the 16 year point as a possible tour length

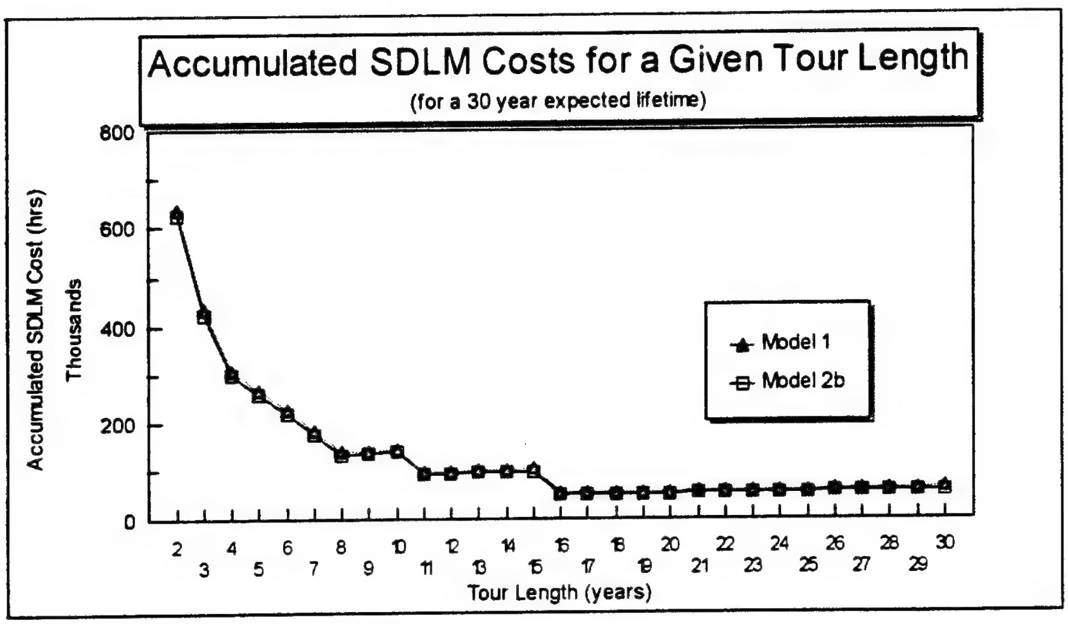

Figure 6. 30 Year Accumulated SDLM Costs. This plot shows the accumulated SDLM costs as a function of tour length during a period of thirty years for a typical E-2C.

since this is not a realistic interval between SDLMs. A tour length of 11 years is probably not a likely tour length to use, specially since the average tour length is 7.7 years. It is important to note however that this tour length is achievable, for example, bureau number 160700 did have an 11 year tour length (see Appendix A for tour lengths of all the E-2Cs inducted into SDLM from fiscal year 1985 to 1994). A tour length of eight years is a local optimal and is only about 4 months longer than the average tour length. The increased cost of doing a SDLM every eight years instead of every 11 years is 41,493 maintenance work-hours over a 30 year lifetime of a typical E-2C.

B. TOTAL LIFE CYCLE COST

In the previous section we examined accumulated SDLM costs over three different expected lifetimes, 20, 25, and 30 years. By means of graphical analysis we discussed various tour lengths that gave us minimal accumulated SDLM costs over each of the three different lifetimes. The accumulated costs did not take into account the current policy regarding scheduled maintenance. The cost of an ASPA was not added into the calculations for accumulated costs. Under the current policy (Chief of Naval Operations, 1993) for an airplane to have a tour length longer than 42 months, it would require a number of ASPA inspections. For example, for an airplane to have a seven year tour, it would require an ASPA inspection every year after the first 42 months until the seven year point -- this would translate into four ASPA inspections. So if we were to do the same analysis as in the previous section adding in the cost of the appropriate number of ASPAs we would have the total cost of the scheduled maintenance program under the current policy. A comparison of the results of this analysis with the results based upon just SDLM costs with no ASPA cost included, we can prescribe an optimal policy for ASPA/SDLM scheduling for the typical E-2C. Data regarding the number of maintenance work-hours spent on each airplane was not available at the time of this study, however, the most recent estimate of the cost of an ASPA inspection was 4000 maintenance work-hours (ASPA meeting minutes, 1991). This cost includes preparing the plane for

inspection (i.e., removing body and wing panels), inspecting the plane, and repairing the discrepancies discovered during the inspection.

Figures 7, 8, and 9 are graphs of accumulated costs as a function of tour length. Values obtained for the graphs followed the same calculations as in the previous section for the accumulated SDLM costs using Model 2b. Plotted on the graphs are both the costs for just SDLMs and the total cost which includes SDLMs and ASPAs. It should be of no surprise that the total cost curve is higher than the SDLM cost curve from the four year point on, since we are just adding 4000 maintenance work-hours to each SDLM for every year the tour length exceeds three. Figures 7, 8, and 9 show that a maintenance policy that includes only SDLMs can be substantially cheaper than a policy that includes both SDLMs and ASPA inspections. For a tour length of 8 years based on a 30 year lifetime, the savings of doing only SDLMs is 60,000 maintenance work-hours for a typical E-2C. But it is arguable that, to have a tour length as long as 8 years, the airplane would

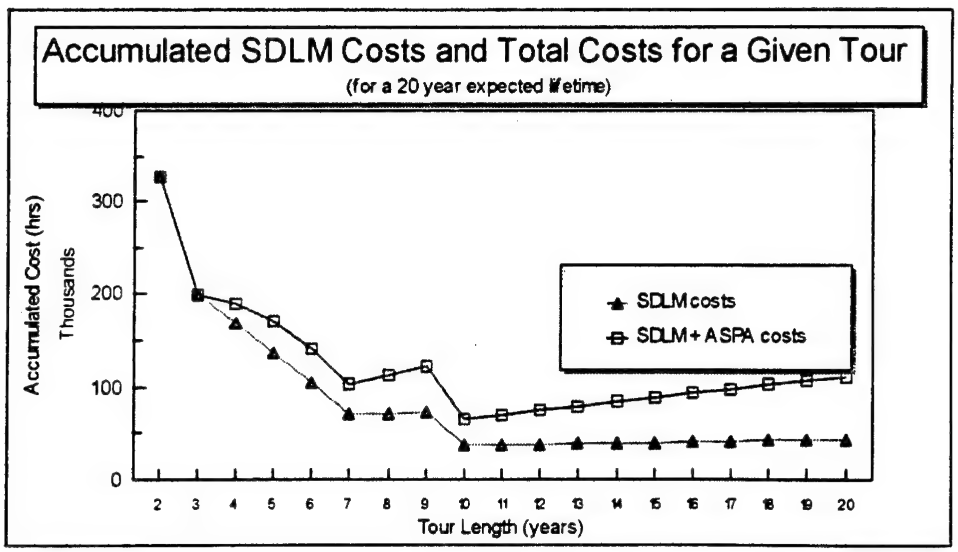

Figure 7. Accumulated Costs for a 20 Year Expected Lifetime. A plot of both accumulated SDLM costs and accumulated SDLM + ASPA costs for a twenty year lifetime of a typical E-2C.

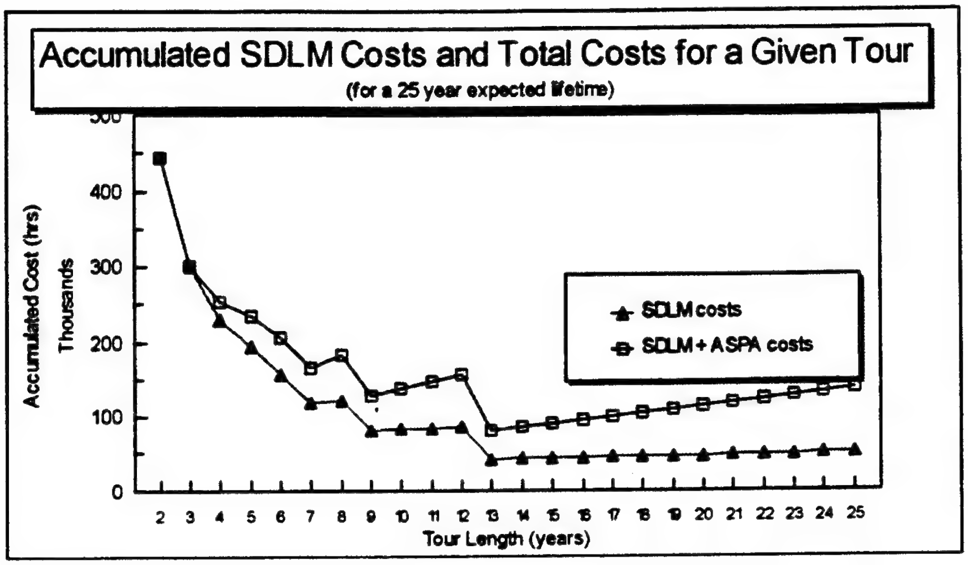

Figure 8. Accumulated Costs for a 25 Year Expected Lifetime. A plot of both accumulated SDLM costs and accumulated SDLM + ASPA costs for a twenty five year lifetime of a typical E-2C.

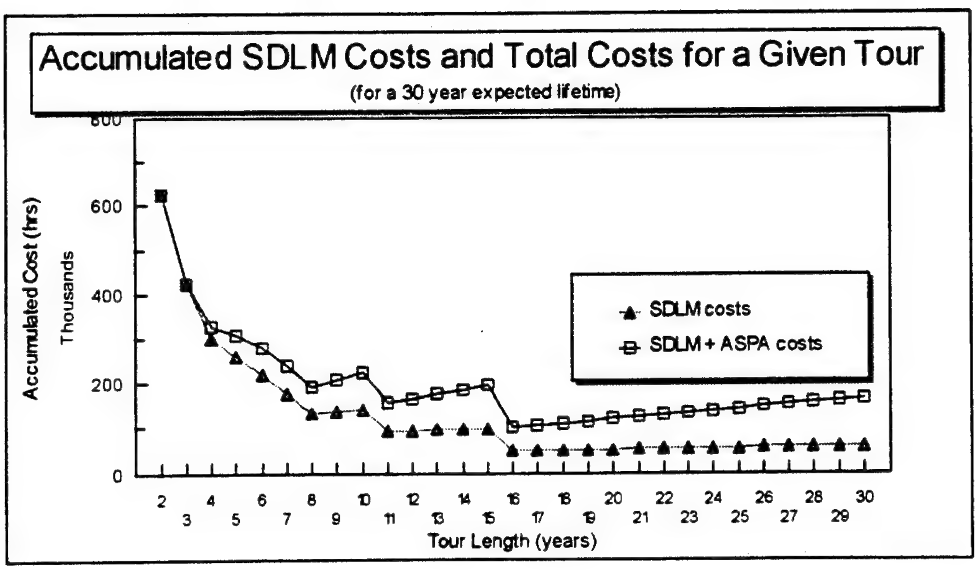

Figure 9. Accumulated Costs for a 30 Year Expected Lifetime. A plot of both accumulated SDLM costs and accumulated SDLM + ASPA costs for a thirty year lifetime of a typical E-2C.

require five ASPA inspections. The ASPA inspections serve a dual purpose. Aside from inspecting the plane for leading indicators of fatigue and wear, it points out to the squadron's maintenance department areas of the airplane that need repaired. Once these areas are repaired the airplane is in better condition than before the ASPA inspection. This repeated squadron level repair could attribute to an increased tour length, like the one seen at the point of structural change mentioned previously. Figures 7, 8, and 9 show an informative cost comparison. Take for example Figure 9. The lifetime cost of performing a SDLM every four years is approximately 290,000 work-hours; to realize a savings in lifetime cost with a program that involved ASPA, the average increase in tour length would have to be at least two years. An ASPA based program with an average tour length of less than six years would have a greater lifetime cost than a program that was based purely on a four year tour length.

C. CONCLUSIONS

The focus of this study was to examine the effects of ASPA on SDLM costs and to show an optimal SDLM/ASPA schedule that would yield the lowest accumulated scheduled maintenance cost over the lifetime of a typical E-2C. The models presented in Chapter IV show how different variables affect SDLM costs. The models show how the effects of these variables change as the ASPA program matures into a steady state. Model 2b definitely shows that the ASPA program played a larger role in increased SDLM costs after it reached a steady state, denoted by the point of structural change, than it did for the first four years after its inception. The only variable in the models that was affected by the ASPA program was the tour length. Pre-structural change, the average tour length was 4.5 years while post-structural change, the tour length had increased to 7.7 years (a 70% increase). The increase in tour length is a direct result of the ASPA program. Holding all other variables in Models 2a and 2b constant, the effect of tour length on SDLM cost doubled while the effect of aircraft age and maintenance work-hours spent on modifications decreased. Although not one of our original goals, these models can also be used to predict the work-hour cost of a particular E-2C that is inducted into SDLM.

The life cycle cost calculations and graphs show several tour lengths that will yield minimal accumulated costs over a given lifetime for a typical E-2C. Each expected lifetime, 20, 25, and 30 years, had two or three optimal tour lengths that produced minimal accumulated costs. These are given to aid the decision maker and are not intended to be used as the only reference when making a decision on tour length. It is important to stress that these optimal tour lengths are for a typical E-2C and may not be the optimal or even appropriate tour length for every airplane. Each airplane will have to be treated on a individual basis. This thesis suggests an optimal policy that is not intended to be a rigid policy which is strictly followed, but a loose policy or set of guidelines that should be obliged when making tour length decisions on each airplane.

Any change in the current maintenance policy will change the predictive value of this thesis. To keep this analysis current, the data base should continue to be added to and analyzed using similar methodology on a yearly basis. The explanatory variable list in the data base should be expanded to encompass variables that were not available and exploited in this thesis. It should be mentioned that simply increasing the number of explanatory variables in the model will not necessarily improve the accuracy of the results. If the analyst does not use discretion when adding explanatory variables to the model, multicollinearity could be induced. A large model could also have an adverse effect on the intuitive insight the model provides by complicating the relationships between the explanatory variables and between the explanatory variables and SDLM cost. Artful simplicity is the rule that should be followed here.

Obviously other factors not mentioned in this thesis should also play a role in the selection of a tour length. Safety of the flight crew should be the most important factor in the determination of an optimal tour length. Other factors such as operational tempo of the squadron should be considered. If a squadron is going to deploy for six months and two of its five airplanes will require an ASPA or SDLM during the deployment, the tour length will obviously need to be shortened or extended to accommodate the deployment schedule. Another possibility is to take two airplanes from another squadron not

scheduled for deployment within a year, thereby making the airplanes available for an ASPA or SDLM.

APPENDIX A. THE DATA SET

	time seq #	buno #	total flt hrs	age (mo)	SDLM #	tour length (mo)	expend SDLM hrs	mods instd	mod expd hrs	expend total hrs
Fiscal Year 85	1	161099	2430	38	1	38	9208	N/A	0	9208
	2	160417	3526	83	2	41	10419	N/A	187	10606
	3	160418	4157	82	2	41	10468	N/A	187	10655
	4	159110	3798	117	3	42	11637	N/A	167	11804
	5	159111	4355	117	3	39	11070	N/A	151	11221
	6	160991	2654	55	1	55	9495	N/A	157	9652
	7	159107	5566	124	3	42	10398	N/A	187	10585
	8	161097	2697	48	1	48	12171	N/A	204	12375
	9	161098	2552	49	1	49	11717	N/A	372	12089
	10	161225	1877	44	1	44	11115	N/A	39	11154
	11	159494	4578	121	3	8	13985	N/A	204	14189
Fiscal Year 86	12	159109	4044	128	3	42	13155	N/A	242	13397
	13	159112	4624	126	3	50	12880	N/A	204	13084
	14	159501	4696	115	3	54	13334	N/A	0	13334
	15	158643	4794	143	3	54	12759	N/A	298	13057
	16	159496	3748	125	3	44	11338	N/A	4	11342
	17	159495	4646	128	3	50	13666	N/A	309	13975
	18	158641	4525	150	4	54	13722	N/A	521	14243
	19	160702	3287	85	2	42	13450	N/A	162	13612

	time seq #	buno #	total flt hrs	age (mo)	SDLM #	tour length (mo)	expend SDLM hrs	mods instd	mod expd hrs	expend total hrs
Fiscal Year 87	20	158640	3625	156	3	47	14758	1	160	14918
	21	160008	4464	122	3	43	13799	3	570	14369
	22	159500	4408	127	3	54	13707	2	570	14277
	23	158638	5810	162	4	45	13360	3	418	13778
	24	159502	4800	128	3	60	13882	5	570	14452
	25	160010	5015	122	3	46	14717	4	870	15587
	26	159498	4866	136	3	55	13722	2	484	14206
	27	158644	5155	157	4	41	13171	1	274	13445
Fiscal Year 88	28	159499	4570	137	3	61	11608	1	312	11920
	29	158645	5050	160	4	46	11502	2	2275	13777
	30	158647	5045	160	4	39	9974	2	2291	12265
	31	159106	5385	158	3	71	13215	2	2455	15670
	32	160009	5044	133	3	53	10212	2	2262	12474
Fiscal Year 89	33	160701	5065	106	2	59	12271	4	2518	14789
	34	161226	3492	72	1	72	16734	N/A	2288	19022
	35	160989	4522	97	2	55	12748	2	2334	15082
	36	161227	3615	73	1	73	11802	N/A	2215	14017
	37	161098	4740	89	2	40	12490	1	2250	14740
	38	160011	5572	144	3	78	17231	2	2626	19857

	time seq #	buno #	total flt hrs	age (mo)	SDLM #	tour length (mo)	expend SDLM hrs	mods instd	mod expd hrs	expend total hrs
Fiscal Year 90	39	160698	5001	124	2	79	14705	7	9267	23972
	40	160987	5026	125	2	82	24252	6	7985	32237
	41	161346	3531	78	1	78	12478	5	6238	18716
	42	159497	6914	171	3	77	22297	6	9144	31441
	43	161095	4896	112	2	71	15076	1	115	15191
Fiscal Year 91	44	159110	5746	175	4	58	25036	12	11361	36397
	45	161343	3820	87	1	87	19621	8	11298	30919
	46	160416	6776	155	3	77	24583	8	6862	31445
	47	161547	4044	86	1	86	24254	7	10351	34605
	48	160699	5249	145	3	83	28962	11	14316	43278
	49	161341	4499	100	1	100	21802	7	11040	32842
Fiscal Year 92	50	160988	5849	135	2	91	35551	16	14136	49687
	51	160697	5480	151	2	108	30640	6	9244	39884
	52	161342	4419	100	1	100	23800	11	19642	43442
	53	161229	4840	105	1	105	19659	7	20886	40545
	54	161549	4475	88	1	88	18168	8	19080	37248
	55	161548	4335	90	1	90	18951	8	22634	41585
	56	160702	5902	149	3	64	20504	5	16747	37251
	57	160420	5897	163	3	87	20950	10	18440	39390
	58	162799	3367	60	1	60	24798	0	0	24798

	time seq #	buno #	total flt hrs	age (mo)	SDLM #	tour length (mo)	expend SDLM hrs	mods instd	mod expd hrs	expend total hrs
Fiscal Year 93	59	160703	5604	147	2	105	21379	8	19393	40772
	60	160991	6031	139	2	84	20841	14	28628	49469
	61	159495	6195	197	4	69	33023	3	3429	36452
	62	160418	7021	168	3	86	33427	3	3725	37152
	63	161099	6294	128	2	90	27943	6	12527	40470
	64	159111	6625	204	4	87	22568	4	12440	35008
	65	161552	4401	92	1	92	29968	7	5087	35055
	66	161550	3927	100	1	100	23577	9	17064	40641
	67	161782	5006	91	1	91	30960	7	3547	34507
	68	159496	6074	205	4	80	31919	1	1093	33012
Fiscal Year 94	69	161344	4454	116	1	116	31172	3	2183	33355
	70	161781	4904	96	1	96	34229	7	4074	38303
	71	161551	3976	105	1	105	38922	9	5225	44147
	72	161780	3978	101	1	101	34625	7	5354	39979
	73	160700	7212	174	2	132	35169	0	0	35169

APPENDIX B. MODEL STATISTICS

1. Model 1

MTB > Retrieve 'C:\THESIS\DATA\FISCAL.MTW'.
MTB > Regress 'SDLM hrs' 4 'tour' 'age' 'mod hrs' 'sinc1945';
SUBC> DW.
The regression equation is
SDLM hrs = - 107117 + 63.3 tour + 13.6 age - 0.314 mod hrs + 2242 sinc1945

Predictor	Coef	Stdev	t-ratio	p
Constant	-107117	15414	-6.95	0.000
tour	63.25	39.79	1.59	0.117
age	13.62	12.80	1.06	0.291
mod hrs	-0.31438	0.08370	-3.76	0.000
sinc1945	2241.7	333.5	6.72	0.000

s = 3824   R-sq = 79.0%   R-sq(adj) = 77.7%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	4	3734126080	933531520	63.83	0.000
Error	68	994470848	14624571		
Total	72	4728596992			

SOURCE	DF	SEQ SS
tour	1	2857471744
age	1	157258064
mod hrs	1	58840816
sinc1945	1	660555520

Unusual Observations

Obs.	tour	SDLM hrs	Fit	Stdev.Fit	Residual	St.Resid
41	78	12478	20210	727	-7732	-2.06R
48	83	28962	21141	801	7821	2.09R
50	91	35551	23809	742	11742	3.13R
58	60	24798	25271	1786	-473	-0.14 X
60	84	20841	21106	1745	-265	-0.08 X
71	105	38922	31571	1101	7351	2.01R
73	132	35169	35861	1996	-692	-0.21 X

R denotes an obs. with a large st. resid.
X denotes an obs. whose X value gives it large influence.
Durbin-Watson statistic = 1.31

2. Model 2a

MTB > Retrieve 'C:\THESIS\DATA\FISEARL2.MTW'.
MTB > Regress 'SDLM hrs' 4 'tour' 'age' 'mod hrs' 'sinc1945';
SUBC> DW.
The regression equation is
SDLM hrs = 8839 + 27.5 tour + 23.5 age + 0.695 mod hrs - 15 sinc1945

Predictor	Coef	Stdev	t-ratio	p
Constant	8839	17272	0.51	0.612
tour	27.51	34.69	0.79	0.432
age	23.54	10.22	2.30	0.027
mod hrs	0.6947	0.1804	3.85	0.000
sinc1945	-15.3	359.5	-0.04	0.966

s = 2243 R-sq = 61.4% R-sq(adj) = 57.6%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	4	320691264	80172816	15.93	0.000
Error	40	201267728	5031693		
Total	44	521958976			

SOURCE	DF	SEQ SS
tour	1	147645104
age	1	62012524
mod hrs	1	111024496
sinc1945	1	9154

Unusual Observations

Obs.	tour	SDLM hrs	Fit	Stdev.Fit	Residual	St.Resid
30	39.0	9974	14457	769	-4483	-2.13R
39	79.0	14705	19526	918	-4821	-2.36R
40	82.0	24252	18741	814	5511	2.64R
44	58.0	25036	21588	1351	3448	1.93 X

R denotes an obs. with a large st. resid.
X denotes an obs. whose X value gives it large influence.

Durbin-Watson statistic = 1.96

3. Model 2b

MTB > Retrieve 'C:\THESIS\DATA\FISLATE2.MTW'.
Retrieving worksheet from file: C:\THESIS\DATA\FISLATE2.MTW
Worksheet was saved on 1/20/1995
MTB > Regress 'SDLM hrs' 4 'tour' 'age' 'mod hrs' 'sinc1945';
SUBC> DW.
The regression equation is
SDLM hrs = - 68670 + 53.7 tour + 13.6 age - 0.480 mod hrs + 1641 sinc1945

Predictor	Coef	Stdev	t-ratio	p
Constant	-68670	51840	-1.32	0.198
tour	53.65	54.56	0.98	0.336
age	13.57	19.14	0.71	0.485
mod hrs	-0.4804	0.1026	-4.68	0.000
sinc1945	1641.4	933.0	1.76	0.092

s = 3820 R-sq = 65.9% R-sq(adj) = 60.0%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	4	648840512	162210128	11.12	0.000
Error	23	335631680	14592682		
Total	27	984472192			

SOURCE	DF	SEQ SS
tour	1	71080344
age	1	36744116
mod hrs	1	495851680
sinc1945	1	45164356

Unusual Observations

Obs.	tour	SDLM hrs	Fit	Stdev.Fit	Residual	St.Resid
5	91	35551	24812	893	10739	2.89R

R denotes an obs. with a large st. resid.

Durbin-Watson statistic = 1.78

APPENDIX C. STRUCTURAL CHANGE

This appendix shows the F-statistic and sensitivity analysis calculations that were used to test for structural change. The following hypotheses and F-statistic are used.

H_0 : the regressions are the same (same intercepts and slopes)

H_a: the regressions are different (at least one slope or intercept is different)

$F = \frac{(ESS_I - ESS_{III}) / (pk-k)}{(ESS_{III}) / (N-pk)}$, where ESS_I and ESS_{III} are the residual sum of squares from the restricted model and unrestricted model respectively and they are divided by the appropriate degrees of freedom.

Figure 1 was examined to determine what visually appeared to be the best place to start applying the above hypothesis testing. The airplanes were numbered sequentially as described in Chapter IV to find the most accurate point of structural change. Testing was done around an initial sequence number that appeared to be the point of structural change and continued until we found the sequence number with the highest F-statistic. This sequence number we determined to be the best place to divide the data into two subsets with the sequence number itself belonging to the second subset. Table 2 shows the results of the sensitivity analysis.

sequence #	test F-statistic	reject H_0
30	0.428	no
32	0.621	no
37	1.114	no
42	1.694	no
47	2.83	yes
48	2.672	yes
46	3.163	yes
45	2.895	yes

This is the best sequence # to split the data into 2 subsets.

APPENDIX D. LONG RUN COST

This appendix shows the calculations that were done to obtain the long run or accumulated SDLM costs and the accumulated total (SDLM + ASPA) costs. The calculations were done on a Lotus 1-2-3 spreadsheet.

1. Accumulated SDLM cost example.

For this example we will use an expected lifetime of a typical E-2C to be 20 years and the tour length to be 12 months. Using Model 2b:

$$SDLM\ cost_{2b} = -68670 + 53.65\ Tour + 13.57\ Age - 0.48\ Mod\ hrs + 1641\ Years\ Since\ 1945,$$

we calculate the accumulated SDLM costs with the following assumptions. Average values of the explanatory variables were calculated over the expected lifetime of the E-2C and put into the model to obtain the cost of an average SDLM over the expected lifetime of an E-2C. This average cost is then multiplied by the number of SDLMs the airplane receives during its expected lifetime to obtain the accumulated SDLM costs. It should be noted in the above equation that the tour length will be fixed while *age* and *years since 1945* will change as the aircraft ages throughout the accumulated SDLM cost analysis. *Mod hrs* will be a function of tour length only, so it will also be a fixed value for each accumulated SDLM cost calculation with a different tour length.

We let *Mod hrs* = 269.79, the average fiscal year work-hours spent per airplane from fiscal years 1985 through 1994. This average work-hour figure was multiplied by the tour length (*tour*) in years, to give the average number of work-hours needed to be spent on the airplane at each SDLM as a result of the tour length: $1(269.79) = 269.79$ work-hours / plane. If the tour length was 24 months vice 12 months *mod hrs* would be multiplied by two.

Accumulated age which is modeled in months is calculated using the finite series sum formula, $Series\ sum = (n)(n-1)/2$. Our assumption of a 20 year lifetime for the E-2C for this example is the value of n in the equation. Since the model requires that age be in

months, the formula is multiplied by 12, so for this example the accumulated age is: $12(20)(21)/2 = 2520$ months. The accumulated age result needs to be divided by the number of SDLMs performed on the airplane over its expected lifetime in order to get the average age at each SDLM.

Years since 1945 will be equal to *50* (to include the years from 1945 until now) plus *10* (the midpoint of the expected lifetime). We now substitute the average values of above explanatory variables in the model to get the average cost of one SDLM. To get the accumulated SDLM cost for a tour length of one year, we multiply the average SDLM cost by the number of SDLMs in the expected lifetime, in this example 20.

$$
\begin{aligned}
SDLM_{acc} &= 20\,\{-68670 + 53.65(12) + 13.57[(12)(20)(21)/2]/20 - 0.48(269.79)(1) \\
&\quad + 1641(50+10)\} \\
&= 640762 \text{ work-hours}
\end{aligned}
$$

2. Accumulated total cost example.

Similar to the calculations for the accumulated SDLM costs, the total cost uses the same assumptions and calculations with one additional cost added. The cost of performing ASPAs must be added to the accumulated SDLM costs. An ASPA is performed when an airplane is due for a SDLM. When a plane comes out of SDLM it is not due for an ASPA inspection for another 42 months (OPNAVINST 3110.11T, 1993). For simplicity, our model will use three years. So for a tour length of five years over an expected lifetime of 20 years, the schedule is shown below. This schedule yields eight ASPA inspections. The cost of an individual ASPA inspection is approximately 4000 work-hours (ASPA meeting minutes, 1991). The total accumulated cost for a tour length of five years over an expected lifetime of 20 years would be the accumulated SDLM cost plus the cost of the eight ASPAs. This calculation is as follows:

$$
\begin{aligned}
Cost_{tot} &= 137684 + 8(4000) \\
&= 169684 \text{ work-hours}
\end{aligned}
$$

year number	SDLM/ASPA
1 - 2	
3 - 4	ASPA (2)
5	SDLM
6 - 7	
8 - 9	ASPA (2)
10	SDLM
11 - 12	
13 - 14	ASPA (2)
15	SDLM
16 - 17	
18 - 19	ASPA (2)
20	SDLM / retire

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Telephone conversation between D. Hodge, Supervisor, 767 Product, Aliance Fort Worth Maintenance Facility, American Airlines, and the author, 7 February 1995.

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